

## 1.6 SURFACE TENSION

### Summary

The recommended values for the surface tension of liquid sodium in  $\text{mN}\cdot\text{m}^{-1}$ , given in Table 1.6-1, are calculated from the Van der Waals equation:

$$\sigma = \sigma_0 \left( 1 - \frac{T}{T_C} \right)^n, \quad (1)$$

where

$$\begin{aligned} \sigma_0 &= 240.5, \\ n &= 1.126, \\ T_C &= 2503.7 \text{ K}. \end{aligned}$$

This equation is based on the analysis by Goldman<sup>(1)</sup> of the available data<sup>(2-16)</sup> from 371 to 1600 K on the surface tension of liquid sodium. The standard deviation of the data from the recommended equation is 5.5%. Thus, the recommended uncertainty ( $\pm 2$  standard deviations) is 11% in the range of experimental data. In the extrapolated region, the estimated uncertainty has been increased to 12%. Figure 1.6-1 shows the recommended values for the surface tension of sodium with the uncertainties as dashed lines. The uncertainties are given in Table 1.6-2.

### Discussion

The recommended equation for the surface tension of sodium was obtained by adjusting the parameters  $\sigma_0$  and  $n$  given by Goldman<sup>(1)</sup> for the recommended critical temperature, 2503.7 K. Goldman used 2509.4 K for the critical temperature in his analysis. The constants recommended by Goldman are:

$$\begin{aligned} \sigma_0 &= 240.7, \\ n &= 1.132, \\ T_C &= 2509.4 \text{ K}. \end{aligned}$$

Thus, the change in the critical temperature changes the constant  $\sigma_0$  by 0.2 (0.08%) and the exponent  $n$  by 0.006 (0.5%). The recommended equation reproduces the values given by Goldman to within 0.07% up to 2000 K. Deviations increase as the critical temperature is approached because the surface tension must be zero at the critical temperature. Deviations of

Table 1.6-1 Surface Tension of Liquid Sodium

Temperature (K)	Surface Tension (mN · m <sup>-1</sup> )
371	200.7
400	197.7
500	187.1
600	176.6
700	166.2
800	155.9
900	145.6
1000	135.4
1100	125.3
1200	115.3
1300	105.4
1400	95.6
1500	85.9
1600	76.3
1700	66.9
1800	57.6
1900	48.5
2000	39.5
2100	30.8
2200	22.4
2300	14.3
2400	6.7
2500	0.2
2503.7	0

the recommended values from those given by Goldman expressed as a percent are shown in Fig. 1.6-2. Deviations are 4% at 2400 K.

In his review of the data on the surface tension of liquid metals, Allen<sup>(17)</sup> recommends using the equation given by Goldman for the surface tension of sodium. However, Allen states that although surface tension near the critical temperature is best described by a Van der Waals equation (Eq. [1]), near the melting temperature, the law of Eötvös gives a better value. The law of Eötvös states that

$$\sigma (Mv)^{2/3} = k (T_C - T) \quad , \quad (2)$$

Table 1.6-2 Uncertainties in the Recommended Values for the Surface Tension of Liquid Sodium

Temperature (K)	$\sigma$ (mN · m <sup>-1</sup> )	Uncertainty, $\left(\frac{\delta\sigma}{\sigma}\right)$ (%)
371 - 1600	$\sigma = \sigma_o \left(1 - \frac{T}{T_c}\right)^n$	11
1600 - 2503.7	<i>where</i> $\sigma_o = 240.5$ $n = 1.126$ $T_c = 2503.7 \text{ K}$	12

where  $M$  is the molecular weight,  $v$  is the specific volume, and  $T_c$  is the critical temperature. Allen recommends  $197.9 \pm 1.8 \text{ mN} \cdot \text{m}^{-1}$  for the surface tension of sodium at its melting point. The recommended equation gives  $200.7 \text{ mN} \cdot \text{m}^{-1}$  at the melting point. Because a single equation is desired for the entire temperature range, the equation given by Goldman adjusted for the critical temperature of 2503.7 K has been selected in accord with the recommendation of Allen.

The data analyzed by Goldman are listed in Table 1.6-3. Three sets of data not included in his nonlinear least squares fit are given at the end of the table. The data of Poindexter and Kernaghan<sup>(14)</sup> were not included in the analysis because no information was reported on the possible contamination of the sample and their value for the surface tension at the melting point is high compared to values from other measurements. Achener's data<sup>(15)</sup> were not included because the large oxygen content of the sodium in these experiments effected the surface tension. In his examination of measurements of the surface tension of alkali metals, Allen<sup>(17)</sup> comments that oxygen impurities in sodium are surface-active. The apparent surface tension is lowered due to formation of an insoluble metal oxide film. Allen's graph of the available data shows that surface tensions measured by Achener are consistently lower than those of other experiments. The data

Table 1.6-3 Surface Tension Data Analyzed by Goldman

Experimenter	Temperature Range (K)	No. of Points	Year	Ref.
Addison et al.	402 - 453	6	1954	2
Addison et al.	383 - 492	27	1955	3
Taylor	411 - 723	30	1955	4
Bradhurst and Buchanan	373 - 523	3	1961	5
Jordan and Lane	473	1	1965	6
Solov'ev and Makarova	467 - 1206	26	1966	7
Bhodansky and Schins	890 - 1128	9	1967	8
Longson and Thorley	396 - 524	20	1967	9
Germer and Mayer	379 - 472	6	1968	10
Roehlich, Tepper and Rankin	414 - 1265	26	1968	11
Todd and Turner	402 - 777	11	1974	12
Chowdhury, Binvignat-Toro and Bonilla	905 - 1593	40	1982	13
Poindexter and Kernaghan <sup>a</sup>	376 - 517	27	1929	14
Achener et al. <sup>a</sup>	541 - 821	47	1969	15
Kirlyanenko and Solov'ev <sup>a</sup>	811 - 1399	27	1970	16

<sup>a</sup>Not included in the least squares fit to the data.

by Kirlyanenko and Solov'ev<sup>(16)</sup> were omitted because their results were not reproducible by the experimenters indicating a difficulty with their measurements. Allen<sup>(17)</sup> cites a subsequent publication of data by Solov'ev and Kirlyanenko<sup>(18)</sup> from the Russian literature in which their difficulty was apparently resolved. The data of Solov'ev and Kirlyanenko<sup>(18)</sup> shown by Allen falls between that of Bohdansky and Schins<sup>(8)</sup> and that of Solov'ev and Makarova.<sup>(7)</sup>

Bystrov et al.<sup>(19)</sup> recommended a cubic equation for the surface tension of sodium from the melting point to 1700 K. It is based on analysis of the available data to 1700 K including 1984 data by Timrot and Reutov<sup>(20)</sup> published in the Russian literature. The deviation of the data from

the equation recommended by Bystrov et al. is 5%. The cubic equation recommended by Bystrov et al. gives  $200.3 \text{ mN}\cdot\text{m}^{-1}$  for the surface tension at the melting point. This value is closer to the value from the recommended equation ( $200.7 \text{ mN}\cdot\text{m}^{-1}$ ) than the value recommended by Allen ( $197.8 \text{ mN}\cdot\text{m}^{-1}$ ). The equation given by Bystrov et al. is not recommended because its cubic form makes it unsuitable for application to the entire temperature range. Values given by this equation are compared with recommended values and those given by Goldman in Fig. 1.6-3. Deviations from recommended values defined as

$$\text{Deviations} = \frac{[\sigma(\text{Other}) - \sigma(\text{Eq. 1})]}{\sigma(\text{Eq. 1})} 100\% \quad (3)$$

are shown in Fig. 1.6-4. The curvature of the deviations of the values by Bystrov et al. is due to the systematic error caused by the use of the different functional form (cubic) to represent the surface tension. The maximum deviation of the values recommended by Bystrov et al. is 5.6% at 1500 K.

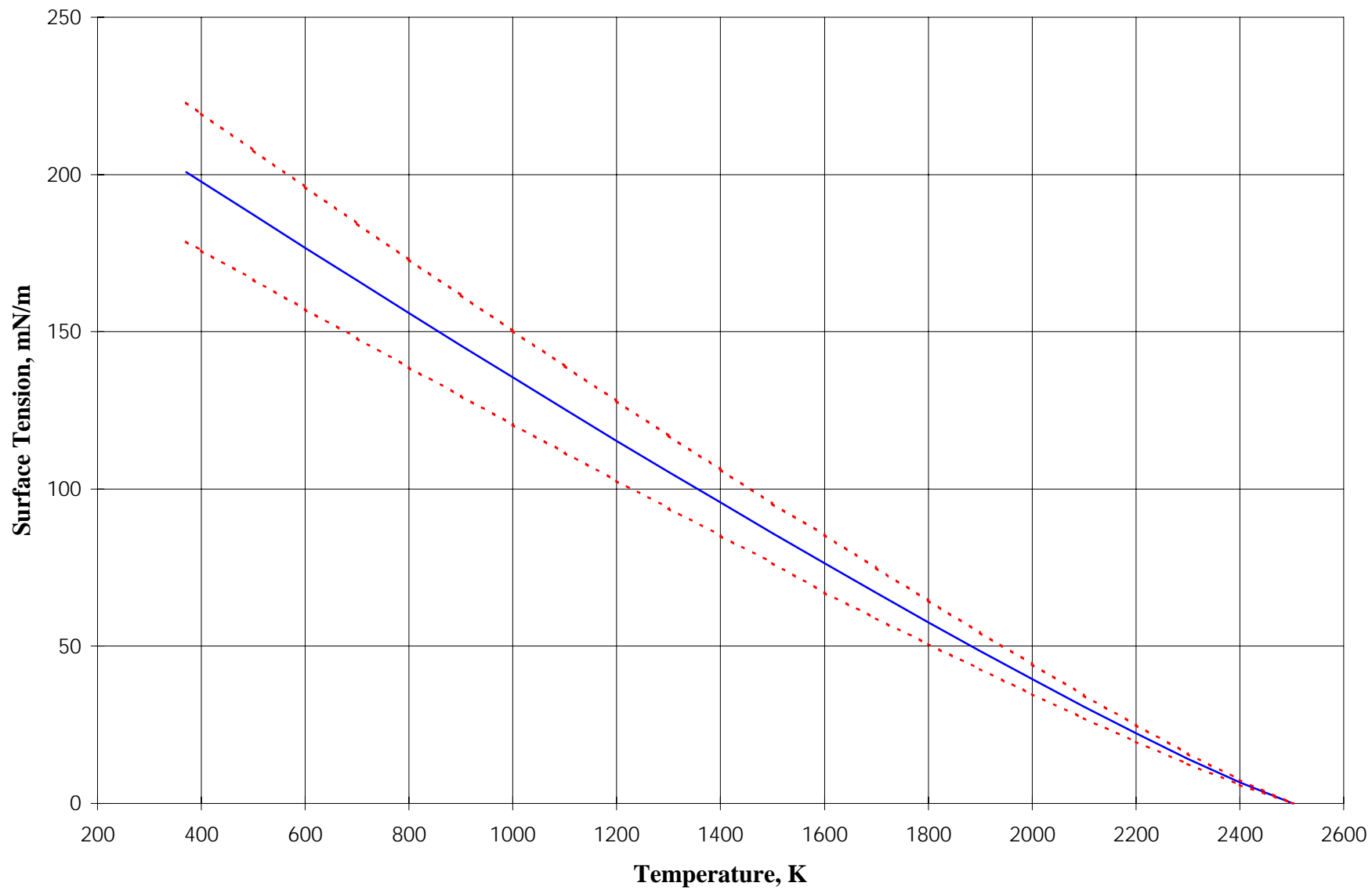
#### Uncertainty

The standard deviation of the data from the recommended equation is 5.5% for the temperature range 371 to 1600 K. Thus, the recommended uncertainty (2 standard deviations) is 11%. Goldman showed that all the data analyzed fall within this error band. Above 1600 K, the estimated uncertainty has been increased to 12%. Although no data are available in this higher temperature region, the error is limited because of the constraint that the surface tension becomes zero at the critical temperature.

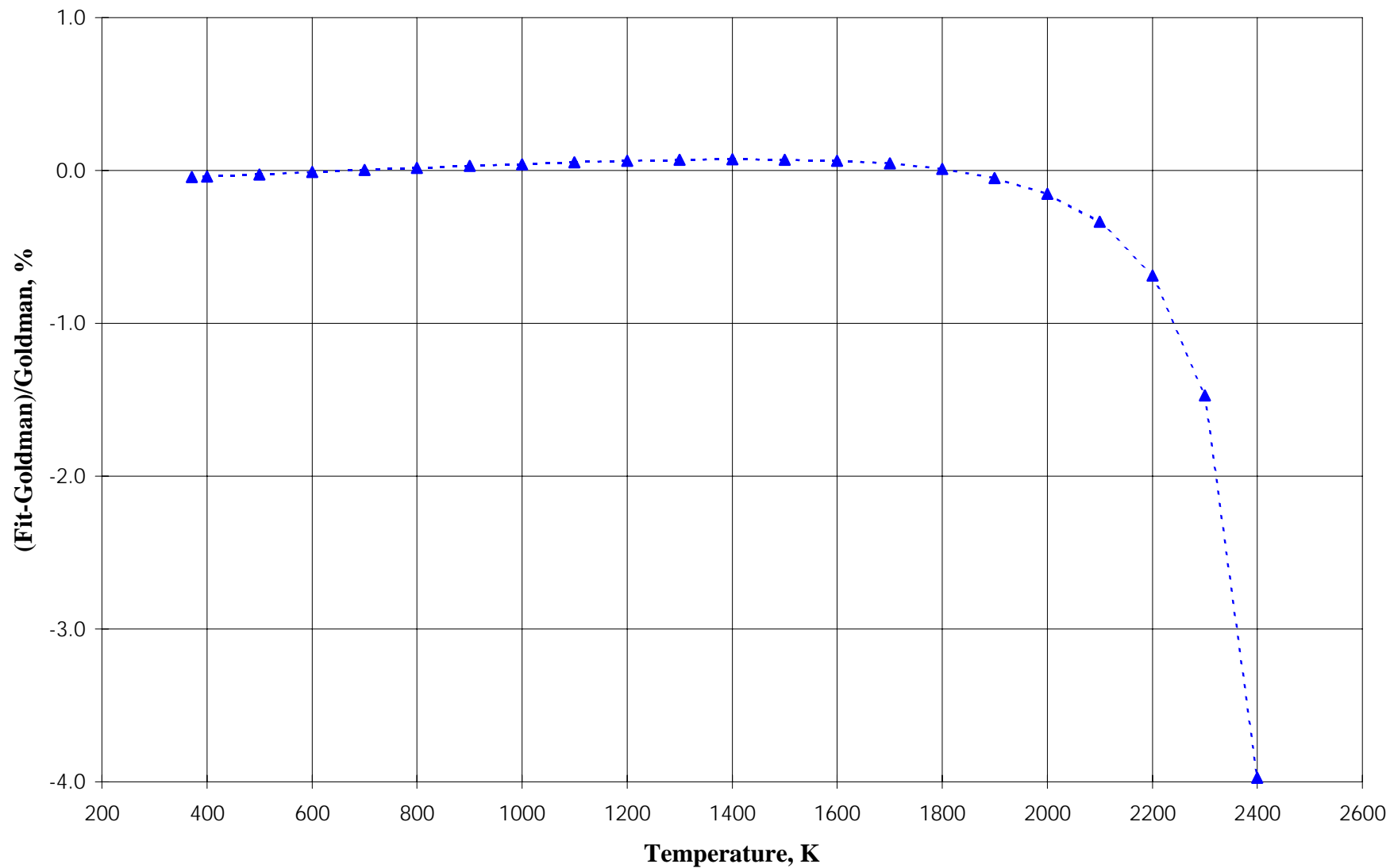
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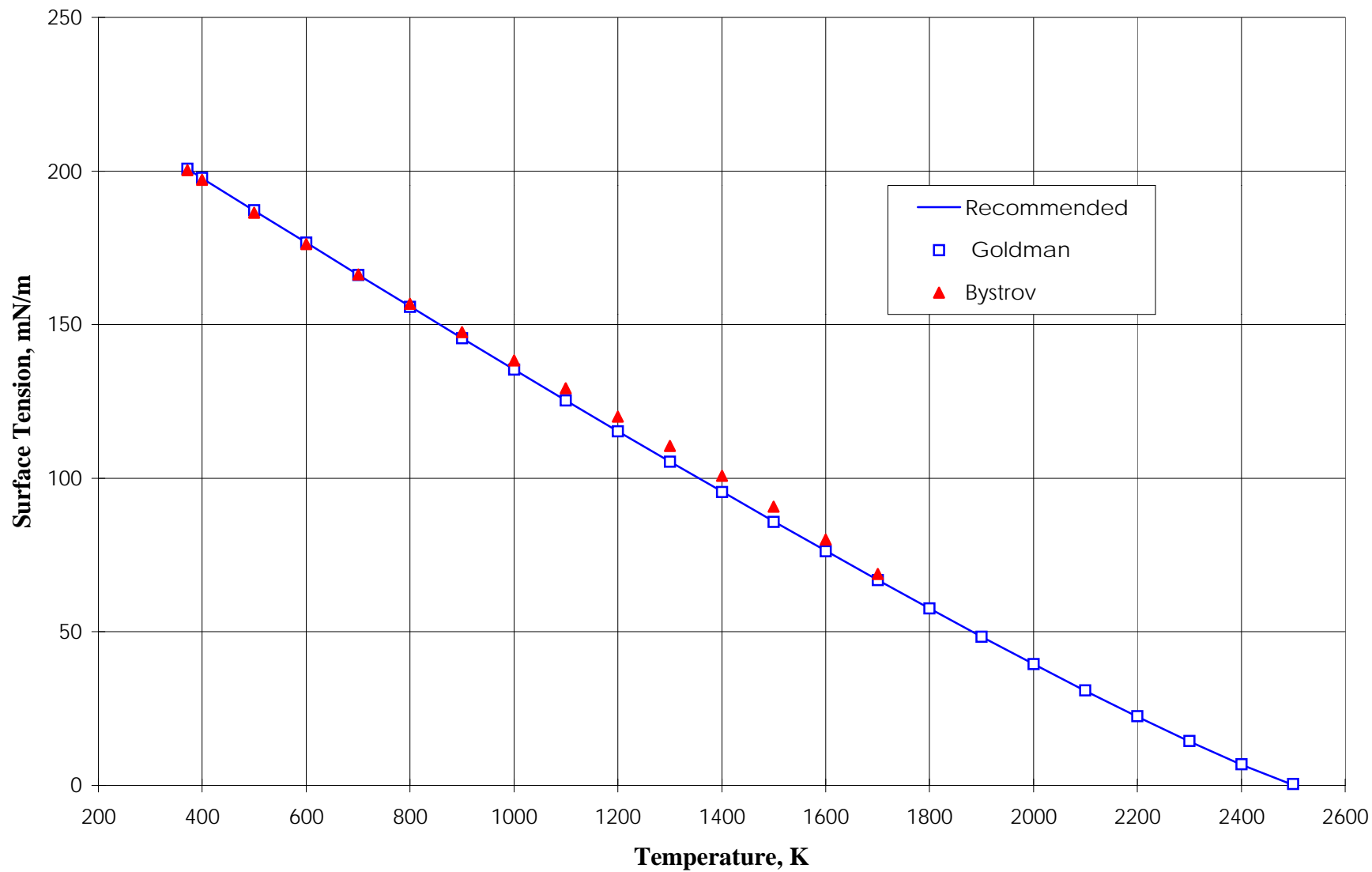
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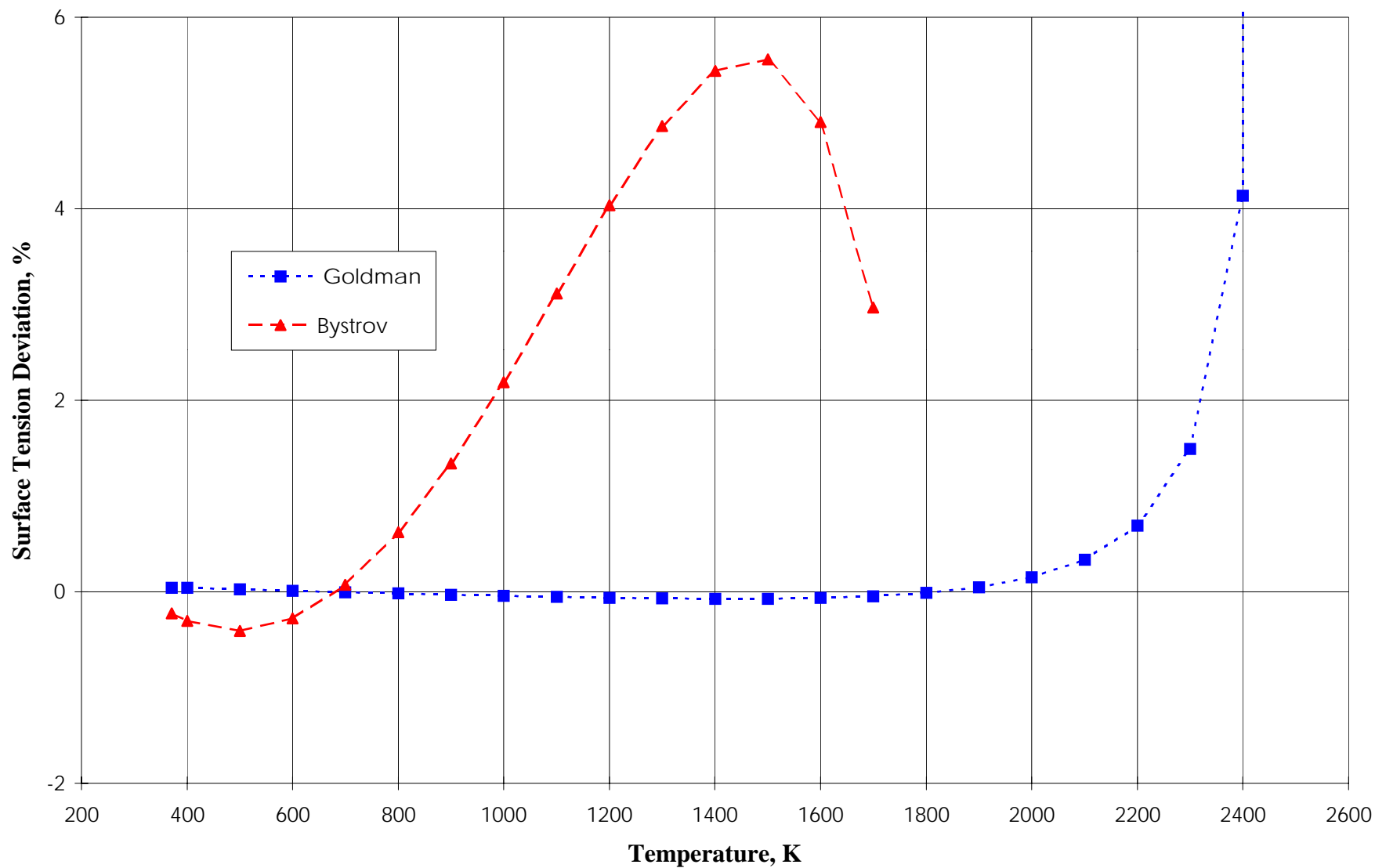
**Fig. 1.6-1 Surface Tension of Liquid Sodium**



**Fig. 1.6-2 Deviations of Recommended Values for the Surface Tension of Sodium from Values Given by Goldman**



**Fig. 1.6-3 Comparison of Recommended Values for the Surface Tension of Sodium with Values of Goldman and of Bystrov et al.**



**Fig. 1.6-4 Deviations of Other Assessments from the Recommended Values for the Surface Tension of Sodium**